

Studies using an airborne laser altimeter to measure landscape properties

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Abstract Vertical surface properties of the landscape were measured using a laser altimeter mounted in a small twin-engine aeroplane. The laser altimeter makes 4000 measurements per second with a vertical recording precision of 0.05 m for a single measurement. These airborne laser measurements were analysed to provide information on topography, vegetation canopy and stream and gully cross-sections. Laser altimeter data were used to measure small (less than 0.20 m deep) and large gullies and stream cross-sections. Vegetation canopy heights, cover, structure and distribution were determined in studies in Texas and Arizona. Laser measurements of vegetation cover and height were significantly correlated with ground measurements made with line-intercept methods. While conventional ground-based techniques may be used to make all these measurements, airborne laser altimeter techniques allow the data to be collected in a quick and efficient way over large and inaccessible areas. The airborne laser altimeter data can also help quantify various land surface parameters needed for natural resource and landscape management or required by hydrological simulation models. Measurements of landscape properties over large areas provide a better understanding of landscape functions and can lead to the development of better management plans to conserve and improve the productivity of natural resources.

Etude des caractéristiques de paysages grâce à un altimètre laser embarqué

Résumé Les propriétés structurales verticales de paysages ont été mesurées grâce à l'utilisation d'un altimètre laser embarqué sur un petit avion bimoteur. L'altimètre laser réalise 4000 mesures par seconde avec une précision de 5 cm. Ces mesures laser aéroportées ont été utilisées afin de fournir des informations concernant la topographie, la couverture

végétale, les sections des cours d'eau et des ravines. Les mesures de l'altimètre laser ont été utilisées pour reconnaître aussi bien de petites (moins de 0.2 m de profondeur) que de grandes sections de cours d'eau et de ravines. La hauteur, la structure et la répartition du couvert végétal ont été déterminées au cours de diverses études menées au Texas et en Arizona. La corrélation entre les mesures laser de la couverture végétale et de sa hauteur et les mesures in situ réalisées selon la méthode de "line-intercept" est significative. Bien que les méthodes conventionnelles de mesure in situ puissent généralement être utilisées pour réaliser ces mesures, les techniques utilisant un altimètre laser embarqué permettent d'obtenir rapidement et efficacement ces données sur de vastes surfaces qui peuvent être inaccessibles. Les données de l'altimètre laser embarqué peuvent également contribuer à la quantification de différents paramètres du paysage nécessaires à sa gestion ou à celle des ressources ainsi qu'à la construction de modèles hydrologiques de simulation. La mesure de caractéristiques des paysages sur de vastes étendues fournit des éléments propres à approfondir nos connaissances concernant leurs fonctions et peut permettre d'améliorer la gestion des ressources naturelles en vue de leur sauvegarde et de l'amélioration de leur rendement.

INTRODUCTION

The Earth's landscape has complex patterns of vegetation and soils on a changing topography (Forman & Godron, 1986). These surface patterns influence the function of the landscape and must be understood and quantified to improve the management of natural resources. The distribution of surface patterns may be mapped from the ground or by using aerial photography or satellite imagery. However, determining the physical properties of these patterns with conventional ground-based technology is difficult, time consuming, often expensive, and usually limited to samples of small areas. This paper discusses studies on the application of airborne laser altimeter data for measuring vertical surface landscape properties and patterns.

Laser technology is used routinely to measure distances along survey lines. When this technology is adapted to aerial surveys (Jepsky, 1986), rapid and accurate assessment of land surface profiles can be made. Airborne laser altimeters have been used for mapping sea ice roughness (Ketchum, 1971), topography (Krabill *et al.*, 1984), vegetation characteristics (Schreier *et al.*, 1985; Nelson *et al.*, 1988; Ritchie *et al.*, 1992), water depths (Penny *et al.*, 1989) and gullies (Ritchie & Jackson, 1989). This paper provides examples of using airborne laser data to study and measure landscape properties.

METHODS AND MATERIALS

A laser altimeter mounted in a twin-engine aeroplane is used to measure the distance from the aeroplane to the landscape surface as defined by any object (i.e., soil, rock, vegetation, man-made structure) reflecting the laser pulse (Ritchie & Jackson, 1989). The altitude of the aeroplane is between 100 and

300 m with speeds from 50 to 100 m per second. The instrument is a pulsed gallium-arsenide diode laser, transmitting and receiving 4000 pulses per second at a wavelength of 904 nm. Under these operating conditions, a laser measurement from the aeroplane to landscape surface occurs at horizontal intervals of 0.0125 to 0.025 m along the flight path depending on the aeroplane speed. The timing mechanism of the laser receiver allows a vertical recording precision of 0.05 m for a single measurement. Under controlled laboratory conditions, the standard deviation of laser measurements of a stationary object is between 0.10 and 0.11 m and is constant for distances between 50 and 300 m.

Digital data from the laser receiver are recorded with a portable computer. Data from a gyroscope and an accelerometer are recorded simultaneously and are used to correct the laser data for aeroplane motion. A video camera, borehole-sighted with the laser, records a visual image of the flight path. A video frame is recorded 60 times per second and each frame is annotated with consecutive numbers and clock time. The video frame number is also recorded simultaneously with the digital laser data to allow precise location of the laser data on the landscape with the video data.

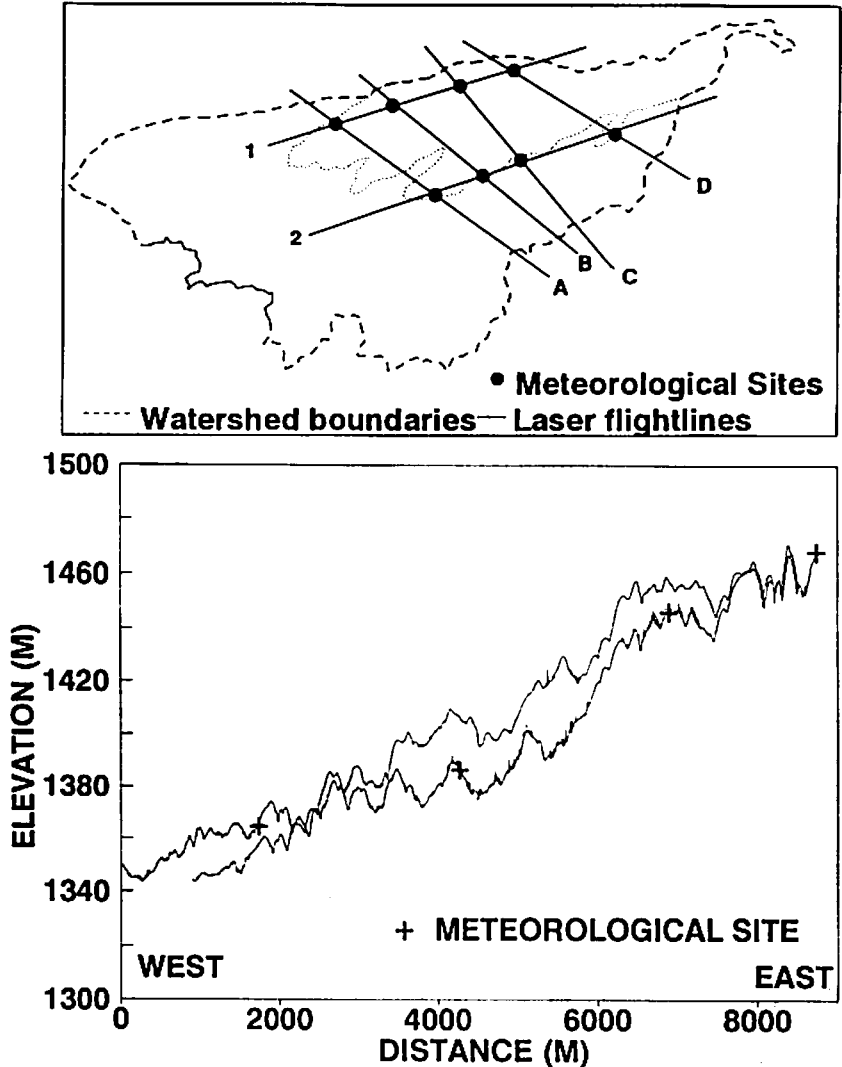
Landscape surface elevation is calculated for each laser measurement based on aircraft motion and known elevations along the flight path. The minimum elevations (maximum laser measurements) along a laser flight path are assumed to be ground surface elevation with measurements above these minima being due to vegetation or man-made structures. In areas of vegetation, the minimum values (ground surface) are estimated by calculating a moving minimum elevation over a preselected number of laser measurements. Manual editing of these minimum elevations is required in areas of dense vegetation cover where too few laser measurements reach the land surface under large canopies.

RESULTS AND DISCUSSION

Several applications of the airborne laser altimeter for measuring landscape parameters are presented. The applications address macro- and micro-scale topography, cross-sections of gullies, streams and flood plains, and measurement of ground vegetation and canopy cover properties.

Macro-topography

Topography of two laser profiles along the same flight path at the Walnut Gulch Research Watershed in Tombstone, Arizona, is shown in Fig. 1. Laser altimeter measurements of the elevations along this west to east flight path ranged from approximately 1340 to 1460 m and closely corresponded to measured elevations at four meteorological stations (Ritchie & Wetz, 1992). The two laser profiles are similar in patterns of elevations but they also show the individuality of each profile. While efforts were made to fly exactly the



Numbers (1 & 2) and letters (A to D) represent location of six different flight lines used for laser measurements

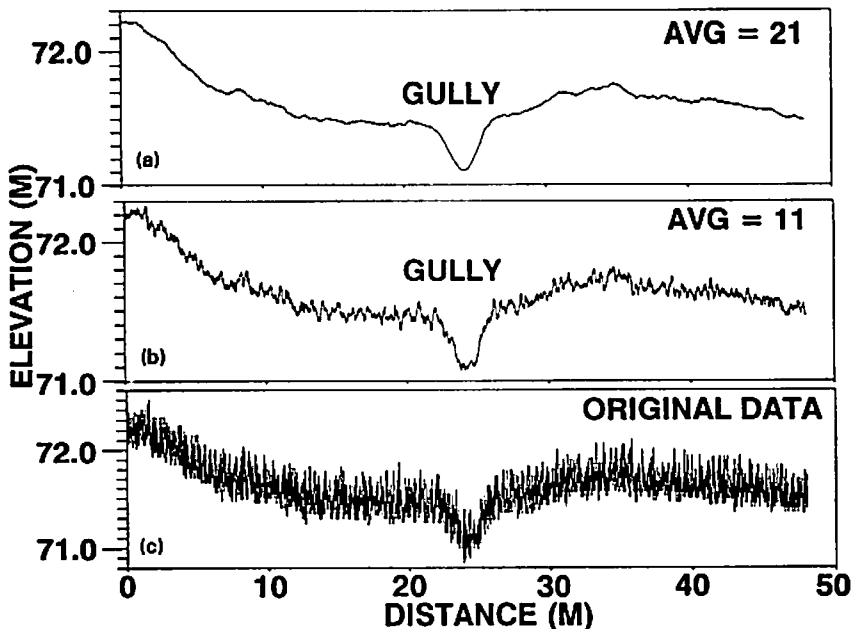
Fig. 1 Laser altimeter profiles of the topography for two paths along flight line 1 at Walnut Gulch Watershed, Tombstone, Arizona.

same path each time, variations in the location of the aeroplane gave each profile a unique pattern of topography. At the east end of the profiles, the aeroplane was close to the same path on both flights resulting in two elevation profiles that match closely. At other points on the line, the aeroplane was over different parts of the landscape. On the video tape made during the flights, markers at the four meteorological stations were visible. One laser profile was consistently north of the markers while the other line was consistently south of the markers. Based on the location of these markers on the video, the two

profiles are estimated to be within 5 to 80 m of each other, horizontally, depending on the location along the line. Since the laser has a footprint of approximately 0.26 m along these profiles, it would be impossible to measure the same ground profile twice with the laser altimeter.

Micro-topography

While the altimeter data lend themselves to the characterization of landscape topography at macro-scales (Fig. 1), analysing altimeter data over short distances gives information on micro-scale topography as shown for a small gully in an agricultural field in Goodwin Creek Watershed, Mississippi (Fig. 2). The actual laser altimeter measurements (Fig. 2(c)) show the variation due to the combination of landscape surface roughness and laser system and random noise. By analysing the data with a moving average filter (McCuen & Snyder, 1986), random and laser system noise can be reduced and systematic variations are easier to see. A moving average over 11 measurements (Fig. 2(b)) removes much of the random variation and reproduces the pattern that represents soil surface roughness, vegetation and topography. A 21-measurement moving average (Fig. 2(a)) removes the micro-roughness patterns and reproduces the pattern of the gully within the general topography. Even though this gully is less



Moving average filters of 11 and 21 points used to improve definition of the features of the gully

Fig. 2 Laser altimeter measurements of a gully in Goodwin Creek Watershed near Oxford, Mississippi.

than 0.40 m deep, it is clearly delineated by the laser data. The choice of the number of measurements to be used in a moving average filter will depend on the information needed for a particular application.

In a study at the Beltsville Agricultural Research Center, Maryland, laser altimeter data were collected at an aeroplane altitude of 200 m over small furrows (gullies) ploughed in a level fallow field (Ritchie & Jackson, 1989). The laser data were analysed using a 21-measurement moving average filter to show the location, depth and cross-section of the furrows. Ground and laser measurements indicated that the furrows were 0.5 to 0.8 m wide and 0.2 to 0.3 m deep. Detailed ground measurements on one furrow were made by taking a photograph of a grid board (10 cm grid) placed in the furrow, and digitizing the furrow shape from the photograph. A comparison of the grid board measurements with laser altimeter measurements (Fig. 3) shows that small furrows (concentrated flow gullies) could be located and measured accurately with airborne laser altimeter data.

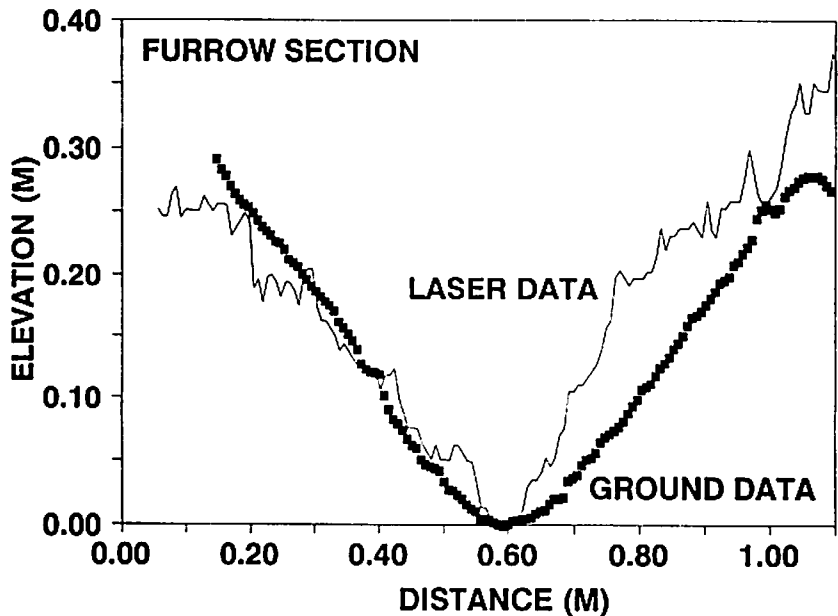
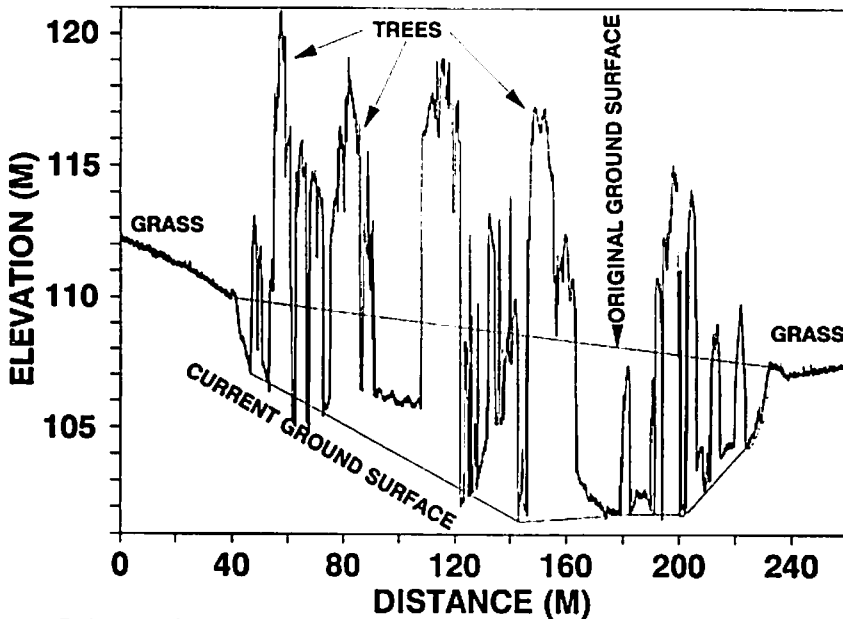


Fig. 3 Comparison of ground and laser altimeter measurements of a furrow (gully) in a level fallow field at the Beltsville Agricultural Research Center, Beltsville, Maryland.

Gullies, streams and flood plains cross-sections

Large erosion scars (gullies) also play an important part in understanding landscape processes. In a study conducted on Goodwin Creek Watershed, Mississippi, laser altimeter data were used to locate and measure the cross-section of a large gully with a partial vegetation cover (Fig. 4). This gully was



Estimates of the location of the current and original ground surfaces shown with dotted lines

Fig. 4 Laser altimeter measurement of the cross section of a gully in Goodwin Creek Watershed near Oxford, Mississippi.

located between two grassed areas. Within the gully scar, 15 to 20 m tall trees were present. By connecting minimum measurements (using moving point minima and best judgement) between tree crowns the "current ground surface" of the gully scar could be estimated. If it is assumed that a straight line between grassed areas represents the original ground surface, an estimate of the area lost due to soil erosion can be made by determining the difference between the current and original ground surface (1035.9 m^2). While arguments can be made for a curvilinear line to represent the original ground surface and a more detailed measurement of the current ground surface, this figure shows how laser altimeter data can be used to estimate the cross-sections of gullies even after they have been partly covered by vegetation.

Cross-sections of gullies or stream channels without vegetation are easier to measure. On the Little Washita Watershed near Chickasha, Oklahoma, the cross-section of a small drainage ditch in a pasture (grass) was measured (Fig. 5). An 11 measurement moving average filter (Fig. 5(a)) of the original data (Fig. 5(c)) was used to improve definition of the topography of the channel. By defining the top of the channel with a straight line, the cross-section of the channel may be measured (Fig. 5(b)). Similar measurements of stream channels of different sizes and shapes have been made, as illustrated in Fig. 6 for a 50 m wide channel in Goodwin Creek Watershed, Mississippi.

Longer segments of laser altimeter data may be used to delineate the topography within the flood plains of streams. Such an altimeter topographic

profile parallel to and then crossing Long Creek, Mississippi, shows a changing pattern of topography (Fig. 7). The profile begins in an agricultural field, intersects two bridges that cross the flood plain of Long Creek, proceeds along a grassed area, intersects an abandoned meander channel of Long Creek, and ends after crossing the flood plain and the current channel of Long Creek.

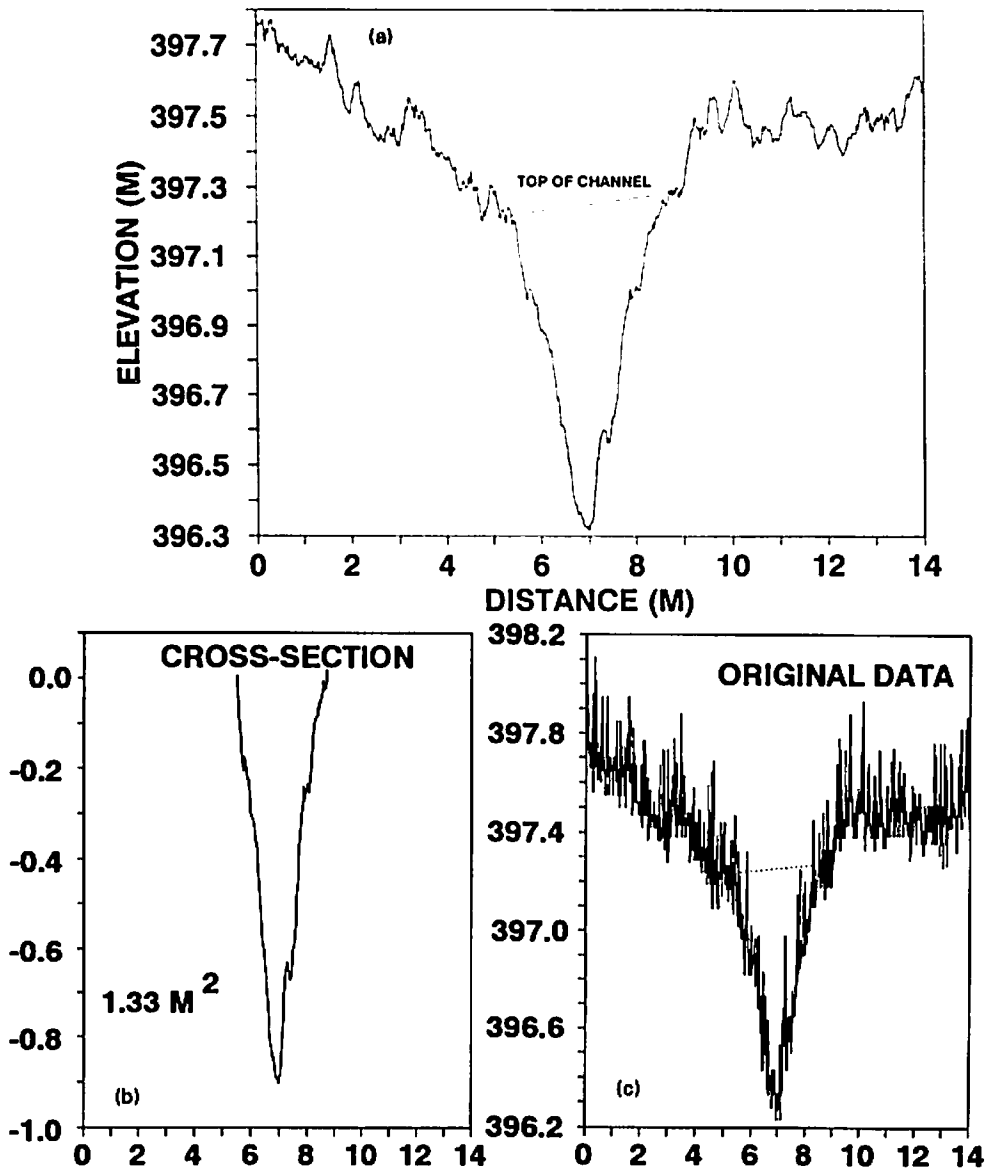


Fig. 5 Laser altimeter measurement of a stream channel in Little Washita Watershed near Chickasha, Oklahoma: (a) data analysed with 21 point moving point filter; (b) channel cross section; and (c) original laser data.

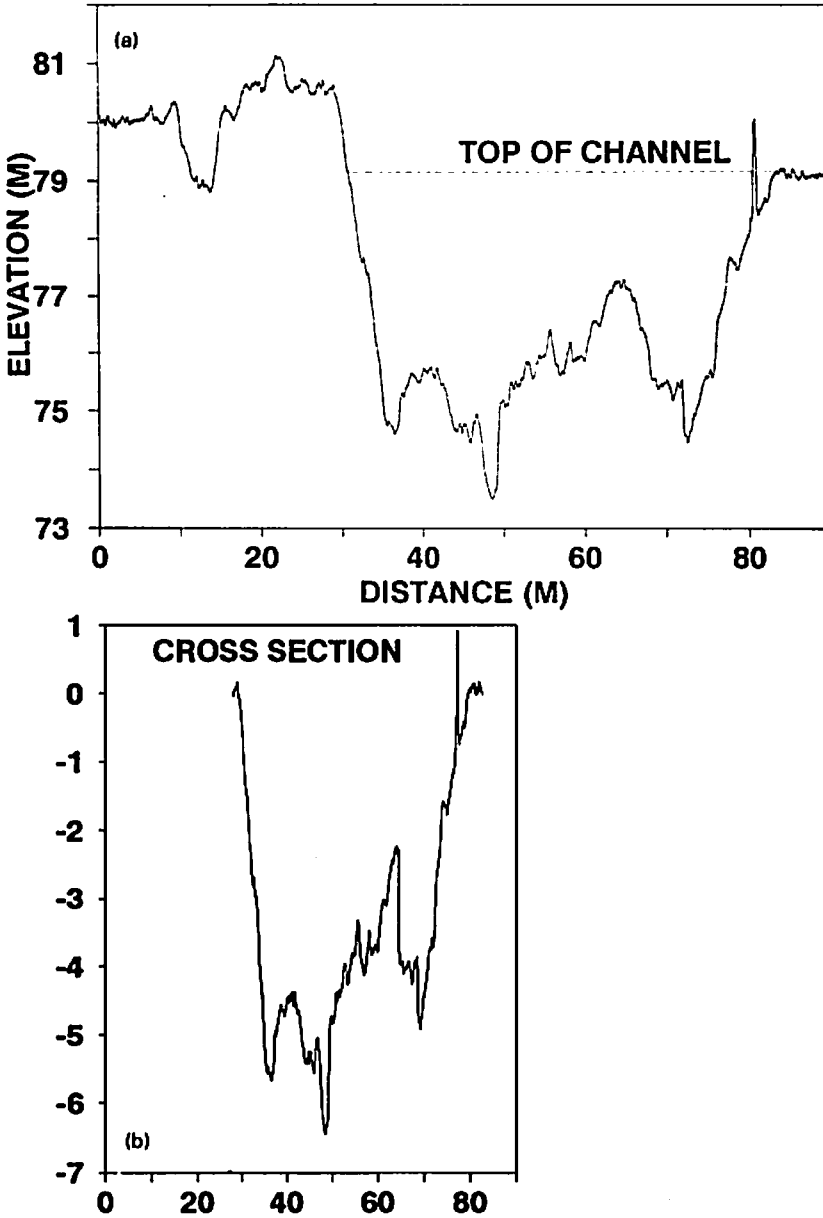


Fig. 6 Laser altimeter measurement of a stream channel (a) and its cross section (b) on Goodwin Creek Watershed near Oxford, Mississippi.

Trees in the flood plain and on the bank of Long Creek are well defined. Such detailed stream cross-section measurements, including associated roughness elements, are tedious and time consuming to measure using traditional field methods. The airborne laser measurements are a quick and accurate approach to define a detailed profile of a cross-section or flood plain. The data can be

used: (a) to determine the channel and flood plain morphology; (b) to quantify the cross-section breakpoint profile; (c) to evaluate the vegetation cover along the section; and (d) to estimate the hydraulic resistance to flow produced by obstacles in the channel and on the flood plain. It is important to note that features that are submerged by water cannot be identified with this laser since the infrared beam does not penetrate water.

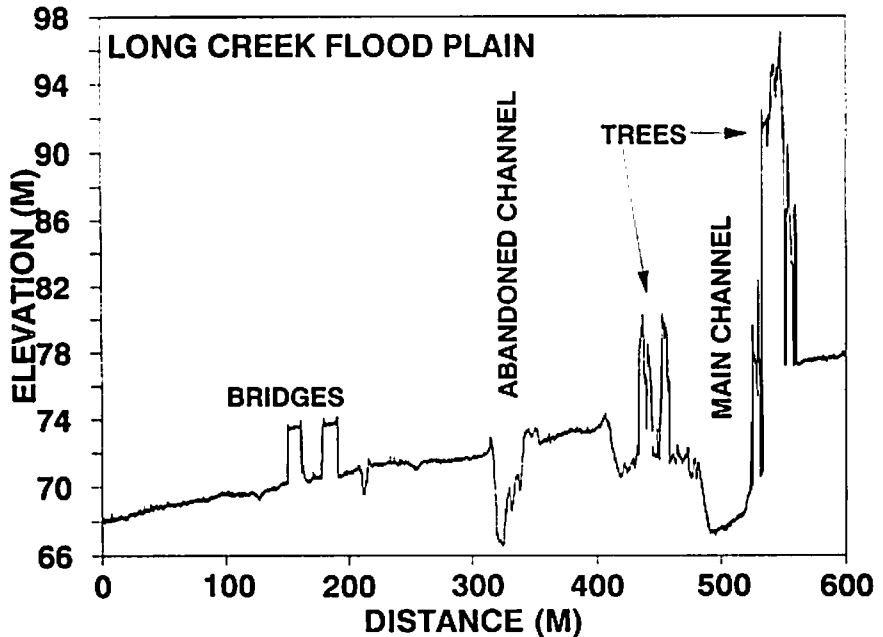
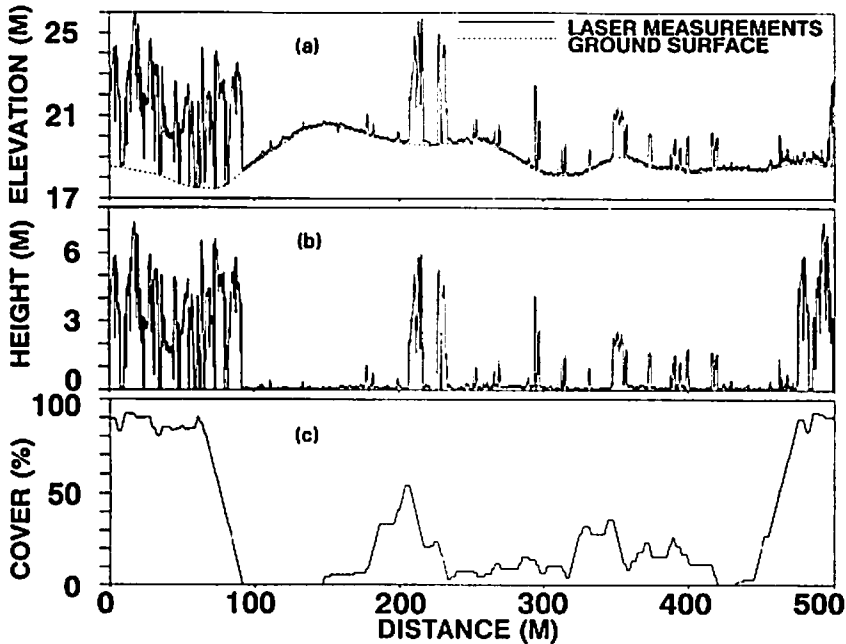


Fig. 7 Laser altimeter measurements of a topographic profile of the flood plain of Long Creek near Batesville, Mississippi.

Vegetation and canopy cover

Vegetation properties of the landscape may also be evaluated from laser altimeter data. In a study of rangeland vegetation in south Texas (Ritchie *et al.*, 1992), laser profiles of the landscape surface (Fig. 8(a)) were analysed to estimate vegetation properties. As with the gully studies described earlier, it was assumed that the minimum elevations represent the ground surface (dotted line) while any measurement above the minimum is due to vegetation. Minimum values were determined by calculating a moving minimum elevation for 21 laser measurements. Manual editing of these minimum elevations is required in areas of dense vegetation cover where too few laser measurements reach the land surface under large canopies. By subtracting the ground elevations (minimum measurements) from the actual laser measurements at a point, the height of the vegetation was determined (Fig. 8(b)). The variation in canopy height and spatial distribution of canopy may also be inferred from the data.

Using the canopy height data (Fig. 8(b)), canopy cover was determined



Ground surface defined by minimum elevations; rangeland vegetation defined by measurements above this ground surface (spikes)

Fig. 8 Laser altimeter measured landscape profile (a), canopy heights (b), and canopy cover for vegetation greater than 0.5 m (c), of a rangeland area near Westlaco, Texas.

for canopy heights greater than 0.5 m by determining the number of laser altimeter measurements greater than 0.5 m (those reflected by canopy elements) and dividing by the total number of laser measurements to determine the canopy cover for the line segment. A spatial pattern of canopy cover was calculated by first determining the percent canopy cover for the first 30.5 m of a flight path, then incrementing one laser measurement or approximately 0.015 m and finally calculating canopy cover for the next 30.5 m. This technique gives a moving average of canopy cover along the flight line for 30.5 m segments (Fig. 8(c)) and shows the distribution pattern for canopy cover greater than 0.5 m. The distribution pattern illustrates the variability in canopy cover for this rangeland area and provides data on shrub distribution on the rangeland.

Ground measurements of canopy cover for 30.5 m lines were made one day after the laser measurements along the rangeland flight line using the line-intercept method (Canfield, 1941; Eberhardt, 1978) and compared with the laser altimeter estimates of canopy cover for the same 30.5 m line segments (Fig. 9). The cluster of data around the 1:1 line shows that ground and laser transects are measuring similar patterns. The correlation coefficient of determination (R^2) was 0.96. The difference between the two methods for any individual comparison was probably due to the inability to measure the same transect on the ground and with the laser. While these comparisons show cover measurements for 30.5 m transects, the laser data could be used to determine

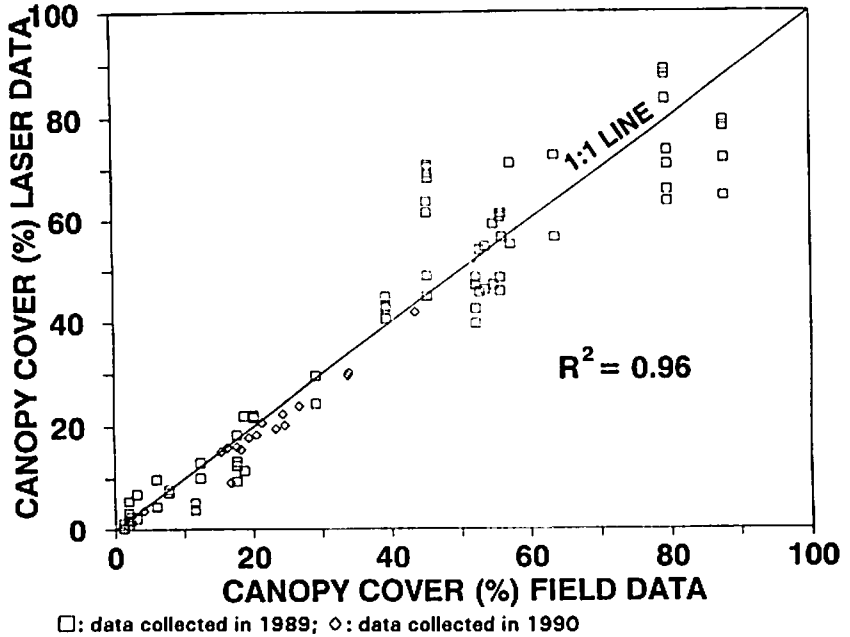


Fig. 9 Relationship between laser and ground measurements of canopy cover for rangeland areas in south Texas.

canopy cover for any length transects. Ground measurement of canopy cover for long transects would be time consuming and costly; thus such ground measurements are seldom made. A similar study of vegetation properties at Walnut Gulch Watershed in Arizona (Fig. 1) found no significant difference between laser and ground measurements of vegetation height and cover (Ritchie & Wertz, 1992). Measurement of vegetation canopy properties over large areas with the laser altimeter is able to provide valuable data for understanding the variability of infiltration, erosion, water movement and other landscape properties. Such data will improve the ability to manage grazing and understand its impact on the landscape.

Using the laser altimeter data collected at Walnut Gulch Watershed, Menenti & Ritchie (1992) have described how to use the laser measurements of mean canopy height, its standard deviation and the penetration frequency of the laser into the canopy, to estimate the effective aerodynamic roughness of a complex landscape. The laser derived estimates of aerodynamic roughness were in good agreement with measurements made using conventional techniques with data from eight meteorological stations in the basin. The laser technique provides an alternative method to estimate aerodynamic roughness. Research is underway at other sites with other vegetation types and densities to determine the general application of laser measurements to estimate aerodynamic roughness. Measurements of the aerodynamic roughness over watersheds will allow a better understanding of the energy flux and the pattern of evapotranspiration at the landscape scale.

CONCLUSIONS

The complex patterns of landscape micro- and macro-topography, drainage features and ground cover are an integral part of the landscape. To improve understanding and management of natural resources on a large scale, one needs to measure and evaluate these landscape features. Measurements of the vertical surface properties of landscapes have been made using an airborne laser altimeter. Several successful applications of the airborne laser altimeter are presented in this paper. The measurements have led to the quantification of landscape topography, vegetation canopy and stream and gully cross-section. Measurements of macro-scale and micro-scale topography contribute to a better quantification of the movement of water over landscape surfaces, in channels and across flood plains. Channel and gully development and degradation may be measured to estimate soil loss and explain water quality and flow problems. Measurements of canopy properties and their distribution across the landscape and their effect on water movement and aerodynamic roughness allow better understanding of evaporative loss as well as of infiltration and surface water movement. Airborne laser altimeters offer the potential to measure landscape properties over large areas quickly and easily. Such measurements provide valuable data for understanding and managing natural resources on a large scale.

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